Gravity Signature of the Teague Ring Impact Structure, Western Australia

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ABSTRACT

As part of an multidisciplinary effort to better define the nature of the Teague Ring structure and to understand specifics about the crustal structure, a GPS controlled gravity survey of the feature was undertaken in the austral winter of 1996. Teague Ring is an impact structure in Western Australia (25° 50' S; 120° 55' E) having a diameter of about 31 km and an age of approximately 1630 Ma. The Bouguer gravity data define an anomaly having an amplitude of 12 mGal and a diameter of about 31 km. The anomaly can be modeled as a mass of low density material extending to a depth of ~5 km with a relative density contrast of -0.13 g cm^{-3}. At Teague Ring the allochthonous and autochthonous large scale breccia is absent having been removed by several kilometers of erosion. Therefore, the low density mass is interpreted to be caused by the fracturing and possibly brecciation of the crystalline basement complex below the surface. The magnitude of the Teague Ring anomaly is consistent with those of other impact structures of similar size.

BACKGROUND

Teague Ring is an impact structure in Western Australia located at 25° 50' S and 120° 55' E (Figures 1 and 2). It has a diameter of 31 km and an age of ~1630 Ma. The diameter is based on the width of interrupted Frere Formation rocks of the Frere Range. The age is loosely constrained on the basis of dates from the crystalline rocks exposed within the structure. Teague Ring was first recognized and described by Butler (1974) and various models of origin have been proposed over the years. Published studies of the structure have only been at the reconnaissance scale. More detailed work was undertaken by Eugene and Carolyn Shoemaker, but it has been published only in limited form (Shoemaker and Shoemaker, 1996).

As part of an multidisciplinary effort to better define the nature of the Teague Ring structure and to understand specifics about the crustal structure, a GPS controlled gravity survey was undertaken in the austral winter of 1996. The objective of the survey was to define the gravity field of Teague Ring, identify any anomaly associated with the structure, and interpret that anomaly in terms of crustal structure.

REGIONAL GEOLOGY

The Teague Ring structure occurs near the unconformable contact between the gently dipping Early Proterozoic sediments of the Nabberu Basin and the underlying crystalline rocks of the Archean Yilgarn Block. Locally, the northwest-trending basement high is referred to as the Wiluna Arch and the Kingston Platform. The Archean crystalline rocks consist of granitic rocks intruded into remnants of greenstone belts. The granitic rocks in the Teague Ring region are medium- to coarse-grained adamellite which exhibit a strong gneissic fabric (Bunting and others, 1980). Exposures of basement are quite limited in the area as the region is characterized by widespread lake deposits and wind-blown material associated with the Lake Nabberu - Lake Teague drainage system. A widespread laterite soil covers the area.

The Early Proterozoic sediments are part of the Earaheedy Group of the Nabberu Basin (Hall and others, 1977; Bunting and others, 1977, 1982). The Earaheedy Group includes eight formations and consists of approximately 6,000 m of shallow water marine sediments. Of this section, only a few units are relevant to the Teague Ring structure and include the Tooloo Subgroup and a part of the Miningarra Subgroup. From oldest to youngest the units near Teague Ring include: the Yelma Formation, Frere Formation, Windidda Formation, Wandiwarra Formation, Princess Ranges Quartzite, and Wongawol Formation.

The Yelma Formation unconformably overlies the basement and is a clastic unit of medium- to coarse-grained quartz arenite, shale, phyllite, and chert with minor stromatolitic carbonate. The Frere Formation, conformable on the Yelma, consists ferruginous sediments and clastics. It is dominated by interbedded banded iron units (granular and banded iron formation) with minor hematitic shale, chert, shale and minor stromatolitic carbonate. The Windidda Formation, which occurs between the Frere and the Wandiwarra, is a carbonate and clastic unit that occurs only to the east in scattered exposures and is not observed within Teague Ring. The overlying Wandiwarra Formation is separated from the lower units by a disconformity. The unit consists of medium- to fine-grained quartz sandstone and shale. The Princess Ranges Quartzite consists of interbedded quartz arenite and minor clayey sandstone and siltstone. The uppermost relevant unit is the Wongawol Formation, a fine-grained arkosic sandstone.

The Earaheedy Group is considered to be Lower Proterozoic in age as it overlies the Archean basement dated at 2.7 to 2.4 Ga (Compston and Arriens, 1968; Roddick and others, 1976; Cooper and others, 1978; Stuckless and others, 1981) and is unconformably overlain by the Bangemall Group which is dated at 1.0 - 1.1 Ga (Compston and Arriens, 1968; Gee and others, 1976). Dates for the Earaheedy units (Horwitz, 1975a; Preiss and others, 1975; Goode and others, 1983) include an age of >1685 Ma for the Wandiwarra Formation (K/Ar on gluaconite) and several analyses for the Yelma Formation which yielded ages of 1590 to >1700 Ma (K/Ar on glauconite; whole rock Rb/Sr; Pb-Pb on galena). Analogies between the Frere banded iron and the Lake Superior banded iron also place the age in the Lower Proterozoic.

GEOLOGY AND STRUCTURE OF TEAGUE RING

Teague Ring is defined on the surface by a ring of the Frere Formation and cored by crystalline Archean granites (Figure 2 and 3). In map view (Bunting and others, 1982) the northwest trend of the Frere rocks (and the Frere Range itself) are interrupted and deformed at Teague Ring. The overall structure is one of a circular syncline cored by uplifted crystalline basement. The collar of Frere Formation rocks form a syncline about 20 km in diameter surrounding a core of crystalline rocks about 13 km in diameter.

Frere Formation rocks form the collar surrounding the crystalline core and the arc of rocks extending from the northwest through the south to southeast side. Northeastward, deformed sediments include the Wongawol Formation, Princess Ranges Quartzite, and Wandiwarra Formation. Units outside the structure have attitudes of gentle northeast dips (5° to 10°) and northwest strikes, whereas within the collar the dips become steep (25° - 75°). On the northeast rim dips are sub-vertical to locally overturned. Dips are shallower and the folding more open to the southwest. In detail, the structure can be quite complex with numerous steeply-dipping tight folds and faults and a general pattern of circumferential shortening and thrusting (Shoemaker and Shoemaker, 1996).

The crystalline rocks within the interior of the structure include quartz syenite and leucogranite (Bunting and others, 1980) and are exposed only in the northeast corner inside the collar of Frere Formation rocks. The leucogranite is medium grained and composed of quartz, albite, and alkali feldspar with minor biotite. The quartz syenite is variable in terms of grain size and mineralogy. Quartz, microcline, plagioclase, sodic pyroxene, and minor sphene, apatite, and zircon occur in varying proportions. The intrusive relations between these two rock types and the overlying Yelma Formation are not observed. However, regional relations and geochronologic data suggest these rocks are part of the crystalline basement and that the Yelma Formation therefore unconformably overlies them.

To the southwest of the structure, a large outcrop of crystalline rock is composed of a hornblende-quartz monzonite composed of quartz, plagioclase, perthitic microcline, and hornblende. Two small outcrops south of the structure include the same hornblende-quartz monzonite and a fine- to medium-grained granite to adamellite.

ORIGIN OF TEAGUE RING

Various modes of origin have been suggested to explain the Teague Ring structure. An evolution of ideas regarding the origin has been fostered by the recognition over the last decade that impact structures are indeed important features of the terrestrial geologic record.

Originally, Butler (1974), in his first description of the structure, suggested Teague Ring could be either an intrusion of the granites exposed in the center, or an impact, although he did not reach a specific conclusion in the brief paper. Horwitz (1975b) mentions Teague Ring only briefly in a summary of the geology of the Yilgarn Block and suggested that it was the result of the interference of mild folds that are typical of the region. Bunting and others (1977), in a discussion of the Lower Proterozoic stratigraphy and structure of the area, proposed that Teague Ring was formed by the cold re-emplacement of a syenite plug at high strain rates, driven by compressive stress associated with the northwest-trending regional folds. Bunting and others (1980) suggested that Teague Ring was formed by the explosion of volatiles related to alkaline magmatism. In each case, only brief mention is made of the structure and no details are provided regarding the suggested mode of origin.

Based on the geologic relations observed at Teague Ring, within the context of a better understanding of the nature of terrestrial impact structures, an impact origin seems the most likely explanation. Shoemaker and Shoemaker (1996) have argued for an impact origin on the basis of the structural style and deformational features observed. Rare shatter cones have been identified in the Frere Formation granular iron strata and a single shatter cone was located within the quartz syenite. Deformation lamellae are observed to occur in quartz from the granitic rocks of the core. Locally, psedotachylite veins occur in the granite and syenite. The structural style of tightly folded strata and inward directed thrusting and shortening are consistent with the deformational style observed in the central peaks of impact structures.

AGE OF TEAGUE RING

Constraints on the age of the structure are provided by geologic relations of the units involved in the deformation and from geochronology of samples. The maximum age of the structure is defined by the age of the Earaheedy Group rocks which are deformed (~1700 Ma). There is, however, no geologic data to provide a minimum age.

Bunting and others (1980) conducted Rb-Sr dating on the crystalline rocks from the core of Teague Ring. Material from 11 sites, 9 from within the structure and two from outside the structure for comparison (5 km south of the structure and 185 km south), were analyzed. The southern-most sample indicates an age of 2,367 Ma for the crystalline basement. The nine samples from within the structure exhibit isochrons indicative of ages of 1,630 Ma and 1,260 Ma.

Bunting and others (1980) consider the 1,630 Ma to be either the original emplacement of the alkali granitoid or a metamorphic event. Shoemaker and Shoemaker

(1996) argue the 1630 Ma probably reflects a resetting age due to the impact, rather than a crystallization age. They argue this point on the basis that the granitic rocks of the interior show shock features; that the age is younger than the overlying Yelma rocks; and that samples of similar rocks from just outside the structure and elsewhere have older radiometric ages of 2,367 Ma. Both Bunting and others (1980) and Shoemaker and Shoemaker (1996) speculate that the 1,260 Ma age is the result of weathering-induced increase in the Rb / Sr ratio. Thus, Teague Ring was already deeply eroded by this time.

COLLECTION AND REDUCTION OF GRAVITY DATA

A gravity survey of the structure was undertaken in August 1996 in order to define the anomaly associated with the structure. An earlier reconnaissance survey conducted in 1986 (Shoemaker and Shoemaker, 1996) defined a significant negative anomaly over the feature. Because of the scale of the structure and the low precision of the topographic maps of the region (Natmap, 1988), the positions of the gravity stations were established by a Global Positioning System (GPS) survey.

Gravity values were measured using a Lacoste Romberg gravity meter (#G-1035). Approximately 140 stations were obtained over the structure. Additional stations were planned, but a malfunction of the meter precluded completion of the survey.

The GPS survey was tied to the one accessible nearby benchmark, NMF-429. Horizontal and vertical control information for this benchmark were provided by the Department of Land Administration, Mapping and Survey Division, Geodetic Survey Services. Because of the remote location of the benchmark, the GPS base station was set up at camp rather than on the benchmark. The GPS base station was tied to the bench mark by occupying the benchmark with a rover station. It is interesting to note that the location for the base station at camp determined by simply averaging the nine days of base station

GPS readings was essentially identical to that determined independently by reference to the benchmark.

Figure 4 shows the location of the gravity stations collected during the survey. The stations were collected along roads or fence lines. Station spacing was approximated at 500 m using the vehicle odometer. Stations on the western edge of the structure across the Frere Range are reconnaissance stations collected in 1986 by Eugene Shoemaker. Locations for the gravity stations were computed by collecting positional information for 10 minutes (600 readings) and differentially correcting the locations after the fact using the camp base station as a reference. The typical standard deviation of the station locations were 0.2 m horizontal N, 0.2 m horizontal E, 0.6 m vertical with a vertical PDOP mean of 3.3. The datum for reduction of the GPS data was AGD 1966 to conform with the 1:250,000 Nabberu topographic map sheet.

Due to the absence of an absolute gravity base within the region, gravity values were tied to an arbitrary base set up at the camp. This base was assigned an absolute value of 979015.76 mGal on the basis of the theoretical value for gravity at this latitude. Base station readings were made approximately every four hours; observed meter drift was of the order 0.007 dial divisions per hour. Reductions were made using the U. S. Geological Survey Bouguer Gravity Program. Corrections made to the data include: latitude, free air, Bouguer, and earth curvature. Terrain corrections were not applied because relief was quite limited (station elevations ranged from 534.1 to 569.1 m: total relief of only 35 m) and topographic maps of the region at sufficient precision to make terrain corrections are lacking. A density of 2.67 g cm^{-3} was assumed for the Bouguer correction. The typical 0.6 m standard deviation mean in the vertical coordinate would result in a corresponding uncertainty of $\pm$ 0.12 mGal in the reduced Bouguer gravity value.

GRAVITY DATA ANALYSIS

The collected data were contoured using a 30 x 30 grid and applying a 1st order polynomial to the data for smoothing to produce the Bouguer gravity anomaly map. For the residual plots, a variable order polynomial surface was applied to the data and a set of residuals calculated which were then contoured. Polynomial surfaces of 1st to 6th order were examined. The 1st order surface, accounting for 46% of the signal, seemed to provide the best illustration of the residual anomaly associated with the feature. Because of the distribution of the data and the heterogeneous density of the basement it is difficult to resolve whether individual short-wavelength features of the gravity field are associated with the structure or the basement. Subtraction of higher order polynomial surfaces results in the creation of numerous local anomalies which do not appear to be associated with the Teague Ring structure.

The simple Bouguer gravity map of the region is illustrated in Figure 5a. A three dimensional view of the same data is presented in Figure 5b. The data show a regional northeastward decreasing gravity field. Typical gradients are just under 1 mGal km^{-1}. Even in the simple Bouguer gravity map, a closed contour low can be seen to be associated with the center of the structure. Beyond the structure, to the northeast, the field appears to flatten or rise slightly, although the data distribution is sparse and the field is poorly constrained in this area. The general gravity decrease from southwest to northeast is consistent with a northward thickening wedge of the Earaheedy Group rocks of the Nabberu Basin overlying the crystalline basement of the Archean Yilgarn Block.

The prominent closed contour low over the structure has approximately 12 mGal of relief. Contours closely parallel the outline of the structure as defined by the 20 km diameter collar of Frere Formation around the core. Isogals are deflected around the structure out a diameter of 31 km, consistent with the dimension of the gap of the northwest-trending Frere Formation (Figure 3). Locally, the contours suggest that the Frere Formation exhibits a local gravity high.

Residual gravity maps of variable order enhance the closed contour low over the center of the Teague Ring structure even more than the Bouguer gravity map. Figure 6 shows the 1st order residual gravity contour map and three dimensional view. This version of the residual data illustrates the closed low of the structure most clearly. These residual maps also indicate that the gravity field is higher outside the structure. In the various residual maps, the minimum gravity observed over the center of the structure is -8 mGal, although locally the relief is as large as 14 mGal. Generally the gravity relief is greater with respect to the area north of the structure than to the south. This difference in relative relief correlates with the surface geology. To the north lies exposures of the Princess Range Quartzite and the Wandiwarra Formation; to the south lies exposures of granite. These data suggest that the quartzites, sandstones, and shales to the north have a relatively higher bulk density.

Within the center of the structure, inside the collar of Frere Formation, quartz syenite and leucogranite out crop. Deflection of the isogals in the residual map along the northern margin within the collar suggest that the quartz syenite exhibits about 1 mGal higher gravity than adjacent lecuogranite, implying it has a slightly higher bulk density than the surrounding core rocks.

GRAVITY MODEL

In an attempt to characterize the subsurface structure of Teague Ring a series of two and half dimensional gravity models were constructed. Detailed modeling is inhibited by the lack of subsurface information and the general lack of physical property data for the rock units in the area. In addition, the widespread cover of Quaternary material hides the details of the basement lithology. Thus, only generalized model can be constructed. However limited, these models can provide some broad constraints on the structure.

The basic elements of the geology that can be incorporated into a gravity model include: the Proterozoic basement of the Yilgarn block; the shallow structural trough of Earaheedy Group rocks along the southern edge of the core; a deeper structural trough of Earaheedy Group rocks along the northern edge which thickens northward into the Nabberu Basin; and a core of crystalline rock in the center of the structure. Using these four basic elements reproduces the general amplitude and shape of the long-wavelength anomaly associated with Teague Ring but misses some of the short-wavelength attributes. Here the modeled anomaly does not completely match the observed data along the southern part of the profile, the model predicts higher gravity than observed. This discrepancy indicates that the structure along the southern side of Teague Ring is more complicated than a simple uniform basement.

Therefore, a more complex model is presented in Figure 7 which better matches both the long- and short-wavelength attributes of the gravity field. This model includes the four elements noted above and two additional bodies. Density contrasts, with respect to the deeper crystalline basement, of the Earaheedy Group rocks (horizontally lined bodies) are -0.07 g cm^{-3}; the density contrast for the material at the center of the structure (stippled body) is -0.13 g cm^{-3}. The two shaded bodies represent aspects of an heterogeneous basement expected for Proterozoic craton material. The body near 0 km has a density contrast of -0.10 g cm^{-3}; the body to the west near 10 km has a density contrast of +0.05 g cm^{-3}. There is no data to indicate the specific nature of these bodies, they may simply represent higher and lower density zones of the crust with respect to the large scale average.

The lack of seismic reflection or refraction data in the region precludes better constraints on the model. The central zone of relatively low density material can be modeled as either a larger body with a relatively low density contract or a smaller body with a higher density contract. The model illustrates a body extending to 5 km depth with a density contract of -0.13 cm^{-3}.

DISCUSSION

The gravity data for Teague Ring clearly define a significant (-12 mGal) anomaly associated with the structure. An anomaly of -12 mGal for Teague Ring, assuming only a 31 km diameter, is consistent with the anomalies associated with other features (Pilkington and Grieve, 1992).

Other impact structures of similar diameters have gravity anomalies comparable to the observed anomaly at Teague. The Mjolnir Structure in the Barents Sea north of Scandinavia is approximately 39 km in diameter. It exhibits an overall negative annular anomaly of about -3 mGal and a central positive anomaly with a gravity relief of about + 4 mGal with respect to depth of the annular low and about +1 mGal with respect to the field outside of the structure (Gudlaugsson, 1993). West Clearwater Lake is one of pair of structures east of Hudson Bay in Quebec Canada. West Clearwater Lake itself has a diameter of about 28 km and contains a ring of islands about 16 km diameter and a cluster six small islands near the center. The central islands and the island ring define the central uplift of the structure. The diameter of the impact structure is estimated at about 32 km. Country rocks of the region are Precambrian granitic to gabbroic gneiss of the Superior Province. A -16 mGal anomaly is associated with the structure (Plante and others, 1990). Finally, the Manson structure in Iowa is approximately 38 km in diameter. It is a well preserved complex crater having a central peak and a structural moat in turn surrounded by a terraced rim. Manson exhibits a central positive anomaly of +4 mGal over the central peak surrounded by an annular negative anomaly of -2 to -4 mGal corresponding to the structural moat and terrace zone (Plescia, 1996). The total gravity relief is of the order 6 to 8 mGal.

Figure 8 illustrates gravity anomalies of other impact structures and the anomaly for Teague Ring. The anomaly associated with Teague Ring is well within the distribution of anomalies from other structures.

The gravity model data (Figure 7) suggest that the central low density body extends to a depth of several kilometers. A thickness of 5 kilometers is illustrated in the model. However, the thickness of the body and the magnitude of the density contrast can be varied to produce the same gravity anomaly. In the model the body extends to 5 km and has a density contract of -0.12 cm^{-3}; however a body extending to a depth of 3 km with a density contrast of -0.17 cm^{-3} would produce the same anomaly. There are no data for Teague Ring to constrain this aspect.

Pilkington and Grieve (1992) summarized density contrasts between fractured and unfractured target rocks for several impact structures. In crystalline terrain, the relatively contrast between the unfractured and fractured basement rocks is between -0.13 and -0.17 g cm^{-3}. If the effects of sediments and breccias are included, the density contrast can reach -0.34 g cm^{-3}. Dyrelius (1988) presented data for the Siljan impact structure in Sweden (~40 km diameter). A drill hole penetrating almost 6 km depth was located inside the structure along its northern edge. Density log data indicate densities of 2.58 to 2.63 g cm^{-3} persisting to a depth of about 5 km. Only at approximately 5.5 km do densities reach a value of 2.67 g cm^{-3} the value considered to be appropriate for the granitic crust of the region. Pohl and others (1977) present data for the Ries Crater in Germany (22 km diameter). There, velocity and density values are reduced below normal to depths of as much as 6 km beneath the present structural level.

Thus a density contrast of -0.13 g cm^{-3} extending to a depth of 5 km for Teague Ring is consistent with data for other similar sized impact structures elsewhere in the world and these values seem reasonable choices for the models.

The diameter of Teague Ring as deduced from either the gravity or the currently exposed geology does not necessarily represent the original diameter of the structure.

Teague Ring is clearly a deeply eroded impact structure and the 31 km diameter represents the extent of the deformation at a structural level below the original surface. Complex impact structures are characterized by a central uplift surrounded by a structurally depressed zone filled with allochthonous and autochthonous breccia in turn surrounded by a faulted terrace zone which marks the edge of the final structure. The original diameter of Teague Ring is uncertain given the current erosional level and the lack of observed details of the geology.

The amount of erosion at Teague Ring can be estimated from two methods, stratigraphy and morphometry. The first is a simple stratigraphic assessment of the thickness of the units involved in the deformation. This is a minimum estimate as it includes only preserved units; higher stratigraphic levels may have been involved in the deformation and completely removed. The highest unit observed within the ring syncline is the Wongawol Formation (observed in a small exposure in the northeast quadrant of the ring syncline). Based on average regional thicknesses of the units below the Wongawol Formation, about 2 to 3 km of erosion would have taken place. The morphometric approach involves the use of a relation presented by Grieve and others (1981) which indicates the degree of structural uplift in the central peak of a complex crater:

$$h_{SU} = 0.06D^{1.1}$$

where h_{SU} represents the structural uplift of the central peak material and D is the diameter of the crater in km. At Teague Ring, the present 31 km diameter would imply an uplift of 2.6 km. As a deformed core of crystalline basement is still exposed, it suggests that the erosion is less than about 2.6 km. Both methods provide crude bounds on the amount of erosion. Taken together they suggest that perhaps 2 km of material has been removed since Teague Ring formed.

In an attempt to assess the original diameter, several approaches can be taken using morphometric and structural comparisons to other structures.

One limit, a maximum, on the diameter can be inferred from the morphometry of the structure. If the assumption is made that the core of crystalline rocks at Teague Ring represents the diameter of the central peak of a complex crater, the post collapse rim-to-rim diameter can be inferred. Studies of craters on the terrestrial planets indicate that the diameter of the central peak approximates:

$$D_{cp} = 0.22\ D$$

(where D_{cp} is the diameter of the central peak and D is the rim-to-rim diameter). The present core diameter is approximately 10 km. From the relation noted above, the original diameter of the Teague Ring structure would have been 45 km. This may not be a relevant comparison however as the transition diameter from craters having central peaks to peak rings is approximately 25 km on the Earth. Thus, even at the presently observed diameter of 31 km, Teague Ring would have been expected to exhibit a peak ring.

An alternative approach to estimating the original diameter is the use of more simple structural comparisons with other large terrestrial structures. The dominant structural element at Teague Ring is the ring syncline having a diameter of 20 km. The position of such a syncline in other structures may be useful in defining the original diameter of Teague Ring. At Upheaval Dome in Utah, the ring syncline axis occurs at a distance of 0.69 of the radius (Kriens, and others, 1997). At the Carswell structure in Canada the axis of the ring syncline occurs at about 0.93 of the radius (Currie, 1969). Large scale explosive craters also show ring synclines. At the Snowball and Prairie Flat tests, each of which was a 500 ton TNT explosion (Roddy, 1977) the ring syncline axis occurs at distances of 0.6 to 0.75 of the radius.

When compared to Carswell, a structural analogy would indicate a diameter of only 22 km clearly smaller than the observed diameter. Analogies to Upheaval Dome would suggest a diameter of about 29 km, again less than the currently observed diameter. Finally, analogies with the large-scale explosion experiments indicate diameters of 27-33 km. There is considerable uncertainty in each of these comparisons and mapping at Teague Ring is only of a reconnaissance nature. However, these comparisons do suggest that although there has been considerable erosion, the original diameter of Teague Ring was probably not significantly greater than its present diameter.

CONCLUSIONS

The Teague Ring structure is a 31 km diameter impact structure in Western Australia. Teague Ring is defined by a annulus of deformed Earaheedy Group rocks, principally the Frere Formation. The structure interrupts the northwest-trending strike of the Frere Range and the deforms the gentle northeast dips of the sedimentary rocks dipping into the Nabberu Basin.

A gravity survey was completed over the Teague Ring structure define an anomaly having an amplitude of 12 mGal and a diameter of approximately 31 km. The anomaly can be modeled as a mass of low density material extending to a depth of approximately 5 km with a relative density contrast of the core material of about -0.13 g cm^{-3}. This low density mass is caused by the fracturing and possibly the brecciation of the crystalline basement complex to several kilometers depth. The magnitude of the Teague Ring anomaly is consistent with those of other impact structures of this size.

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REFERENCES

Bunting, J. A., Brakel, A. T., and Commander, D. P., 1982, Nabberu Western Australia, 1:250,000 Geologic Series - Explanatory Notes, 27 pp. Geological Survey of Western Australia, Sheet SG/51-5.

Bunting, J. A., Commander, D. P., and Gee, R. D., 1977, Preliminary Synthesis of Lower Proterozoic Stratigraphy and Structure Adjacent to the Northern Margin of the Yilgarn Block, Western Australia Geological Survey Annual Report 1976, p. 43-48.

Bunting, J. A., de Laeter, J. R., and Libby, W. G., 1980, Evidence for the Age and Cryptoexplosive origin of the Teague Ring Structure, Western Australia, Report of the Department of Mines, Western Australia for the Year 1979 Annual Report, p. 125-129.

Butler, H., 1974, The Lake Teague Ring Structure, Western Australia: An Astrobleme? Search, v. 5, p. 533-534.

Compston, W., and Arriens, P. A, 1968, The Precambrian geochronology of Australia, Canadian Journal of Earth Science, v. 5, p. 561-583.

Cooper, J. A., Nesbitt, R. W., Platt, J. P., and Mortimer, G. E., 1978, Crustal development in the Agnew region, Western Australia, as shown by Rb-Sr isotopic and geochemical studies, Precambrian Research, v. 7, p. 31-59.

Currie, K. L., 1969, Geological notes on the Carswell circular structure, Saskatchewan, Geological Survey of Canada, Paper 67-32, 60 pp.

Dyrelius, D., 1988, The gravity field of the Siljan ring structure, in Deep Drilling In Crystalline Bedrock, vol. 1., The Deep Gas Drilling in the Siljan Impact Structure, Sweden and Astroblemes, edited by A. Boden and K. G. Eriksson, pp. 85-94, Springer-Verlag, New York.

Gudlaugsson, S. T., 1993, Large impact crater in the Barents Sea, Geology, v. 21, p. 291-294.

Gee, R. D., de Laeter, J. R., and Drake, J. R., 1976, Geology and geochronology of altered rhyolite from the lower part of the Bangemall Group near Tangadee, Western Australia, Western Australia Geological Survey Annual Report 1975, p. 112-117.

Goode, A. D. R., Hall, W. D. M., and Bunting, J. A., 1983, The Nabberu Basin of Western Australia, *in* Trendall, A. F., and Morris, R. C., eds., Iron-formations: Facts and Problems, Elsevier, Amsterdam, pp. 295-325.

Hall, W. D. M., Goode, A. D. T., Bunting, J. A., and Commander, D. P., 1977, Stratigraphic Terminology of the Earaheedy Group, Nabberu Basin, Western Australia Geological Survey Annual Report 1976, p. 40-43.

Horwitz, R. C., 1975a, The southern boundaries of the Hamersley and Bangemall Basins of sedimentation, Geological Society of Australia, First Australian Geological Convention, Adelaide, Proterozoic Geology, p. 91.

Horwitz, R. C., 1975b, Provisional geology map at 1:250,000 of the north-east margin of the Yilgarn Block, Western Australia. Australia CSIRO Mineral Research Laboratory Report F. P. 10.

Hall, W. D. M., and Goode, A. D. T., 1978, The Early Proterozoic Nabberu Basin and Associated Iron Formations of Western Australia, Precambrian Research, v. 7, p. 129-184.

Kriens, B. J., Herkenhoff, K. E., and Shoemaker, E. M, 1997, Structure and kinematics of a complex crater: Upheaval Dome, southeast Utah, (abstract), in Large Meteorite Impact and Planetary Evolution. LPI Contribution No. 922, Lunar and Planetary Institute, Houston, p. 29-30.

Natmap, 1988, Nabberu Sheet, Sheet SG 51-1, 1:250,000 Scale, National Topographic Map Series.

Pilkington, M., and Grieve, R. A. F., 1992, The geophysical signature of terrestrial impact craters, Reviews of Geophysics, v. 30, p. 161-181.

Plante, L., Seguin, M. K., and Rondot, J., 1990, Etude gravimetrique des astroblems du Lac a l'Eau Clari, Nouveua Quebec, Geoexploration, v. 26, p. 303-323.

Plescia, J. B., 1996, Gravity investigation of the Manson impact structure, Iowa, *in* Koeberl, C., and Anderson, R. R., eds., The Manson Impact Structure, Iowa: Anatomy of an Impact Crater: Boulder, Colorado, Geological Society of America Special Paper 302, p. 89-104.

Pohl, J., Stoffler, D., Gall, H., and Ernstson, K., 1977, The Ries impact crater, *in* Roddy, D. J., Pepin, R. O., and Merrill, R. B., eds., Impact and Explosion Cratering, Pergamon Press, p. 343-404.

Preiss, W. V., Jackson, M. J., Page, R. W., and Compston, W., 1975, Regional Geology, stromatolite biostratigraphy and isotopic data bearing on the age of a Precambrian sequence near Lake Carnegie, Western Australia, Geological Society of Australia, First Australian Geological Convention, Adelaide, Proterozoic Geology, p. 92-93.

Roddick, J. C., Compston, W., and Durney, D. W., 1976, The radiometric age of the Mount Keith Granodiorite, a maximum age estimate for an Archean greenstone sequence in the Yilgarn Block, Western Australia, Precambrian Research, v. 3, p. 55-78.

Roddy, D. J., 1977, Large-scale impact and explosion craters: Comparisons of morphological and structural analogs, *in* Roddy, D. J., Pepin, R. O., and Merrill, R. B., eds., Impact and Explosion Cratering, Pergamon Press, p. 185-246.

Shoemaker, E. M., and Shoemaker, C. S., 1996, The Proterozoic impact record of Australia, AGSO Journal of Australian Geology and Geophysics, v. 16, p. 379-398.

Stuckless, J. S., Bunting, J. A., and Nkomo, I. T., 1981, U-Th-Pb systematics of some granitoids from the northeastern Yilgarn Block, Western Australia and implications for uranium source potential, Journal Geological Society of Australia, v. 28, p. 365-375.

FIGURE CAPTIONS

Figure 1. Map of Australia showing location of Teague Ring and several other major impact structures.

Figure 2. Oblique Space Shuttle image of Teague Ring structure. View to the northwest. White areas are playa surfaces of the Lake Teague / Lake Nabberu system. Dark band extending from lower right to upper left is the Frere Range, dominated by the Frere Formation banded iron units.

Figure 3. Geology of Teague Ring structure. Adapted from Bunting and others (1982). *Revised figure to be submitted.*

Figure 4. Map indicating gravity station locations. Station locations indicated by (+).

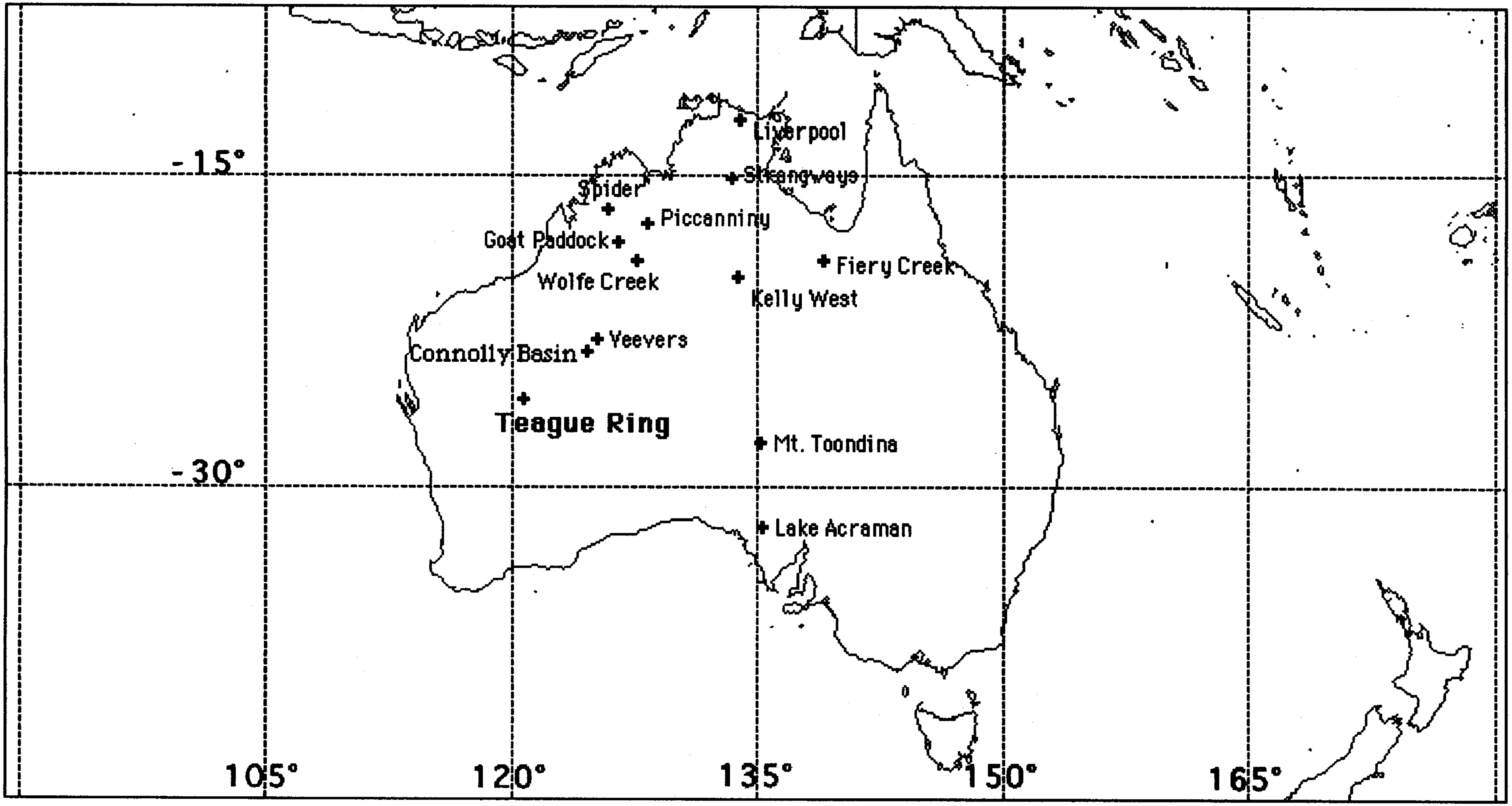
Figure 5. (a) Simple Bouguer gravity map of the Teague Ring structure. Contour interval is 2 mGal. Crosses indicate station locations. (b) Three dimensional view of the Bouguer gravity field.

Figure 6. (a) First order residual gravity map of the Teague Ring structure. Contour interval is 2 mGal. Crosses indicate station locations. (b) Three dimensional view of the first order residual gravity field.

Figure 7. Two and half dimensional gravity model of the Teague Ring structure. Profile is oriented in a northeast-southwest direction. Small circles indicate measured gravity values; the line indicates the modeled gravity. Numbers denote the relative densities for the bodies

in g cm^{-3} relative to the basement. Horizontally striped bodies are Earaheedy Group rocks; the stippled body represents the low-density core material; shaded bodies represent density anomalies within the crystalline crust. Vertical exaggeration is 2X.

Figure 8. Gravity anomalies of impact structures plotted as a function of the diameter. Anomalies for Teague Ring denoted by an open circle (o); other craters are indicated by a triangle.



Liverpool
Strangways
Spider
Piccaninny
Goat Paddock
Wolfe Creek
Fiery Creek
Kelly West
Yeevers
Connolly Basin
Teague Ring
Mt. Toondina
Lake Acraman
-15°
-30°
105°
120°
135°
150°
165°

Figure 2

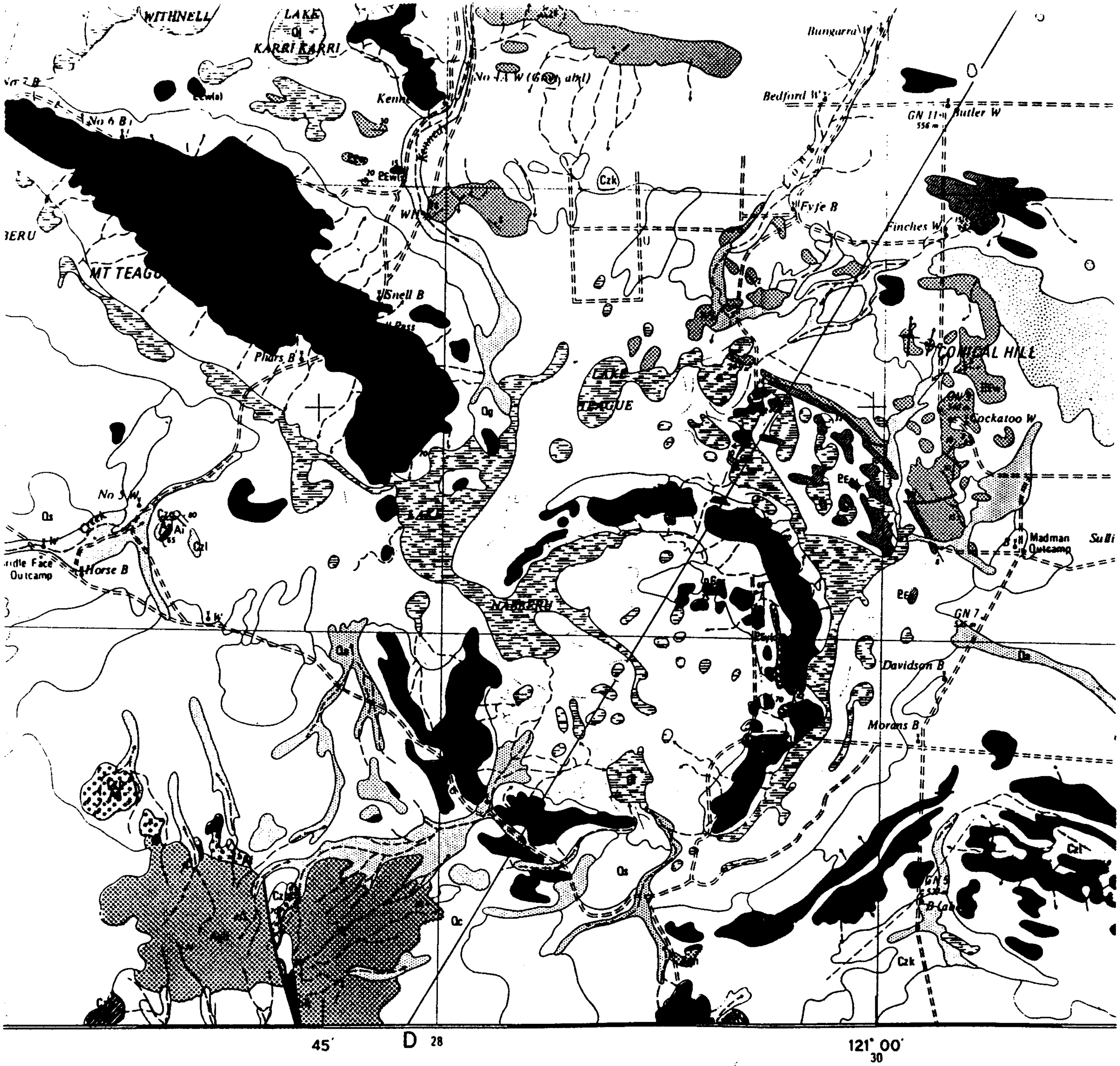

WITHNELL
LAKE
KARRI KARRI
MT TEAGUE
LAKE
TEAGUE
NABBERU
CONICAL HILL
Bungarra W
Bedford W
Butler W
Fyfe B
Finches W
Cockatoo W
Madman
Outcamp
Snell B
Phars B
No 6 B
No 5 W
Horse B
Davidson B
Morans B
GN 7
Czk
Czl
Qs
Qa
Qc
45′
D
28
121° 00′
30

Figure 3

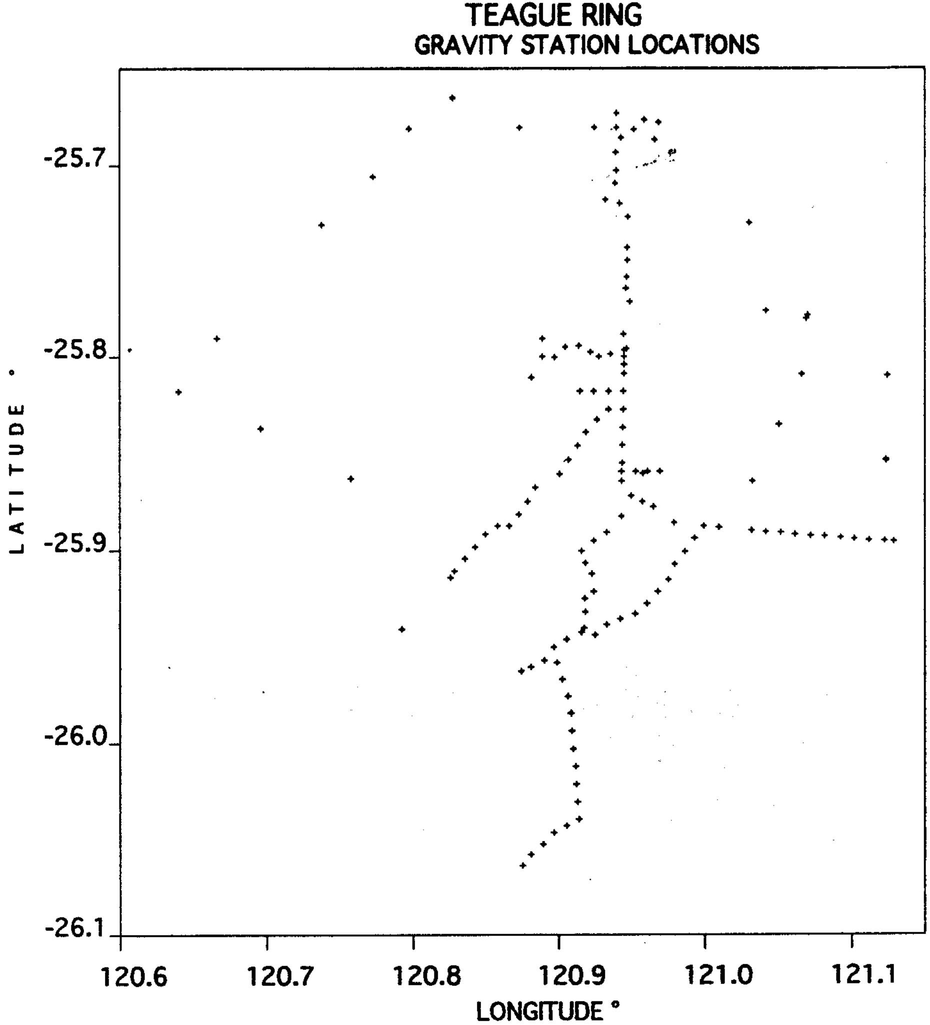

TEAGUE RING
GRAVITY STATION LOCATIONS
LATITUDE °
-25.7
-25.8
-25.9
-26.0
-26.1
120.6
120.7
120.8
120.9
121.0
121.1
LONGITUDE °

Figure 4

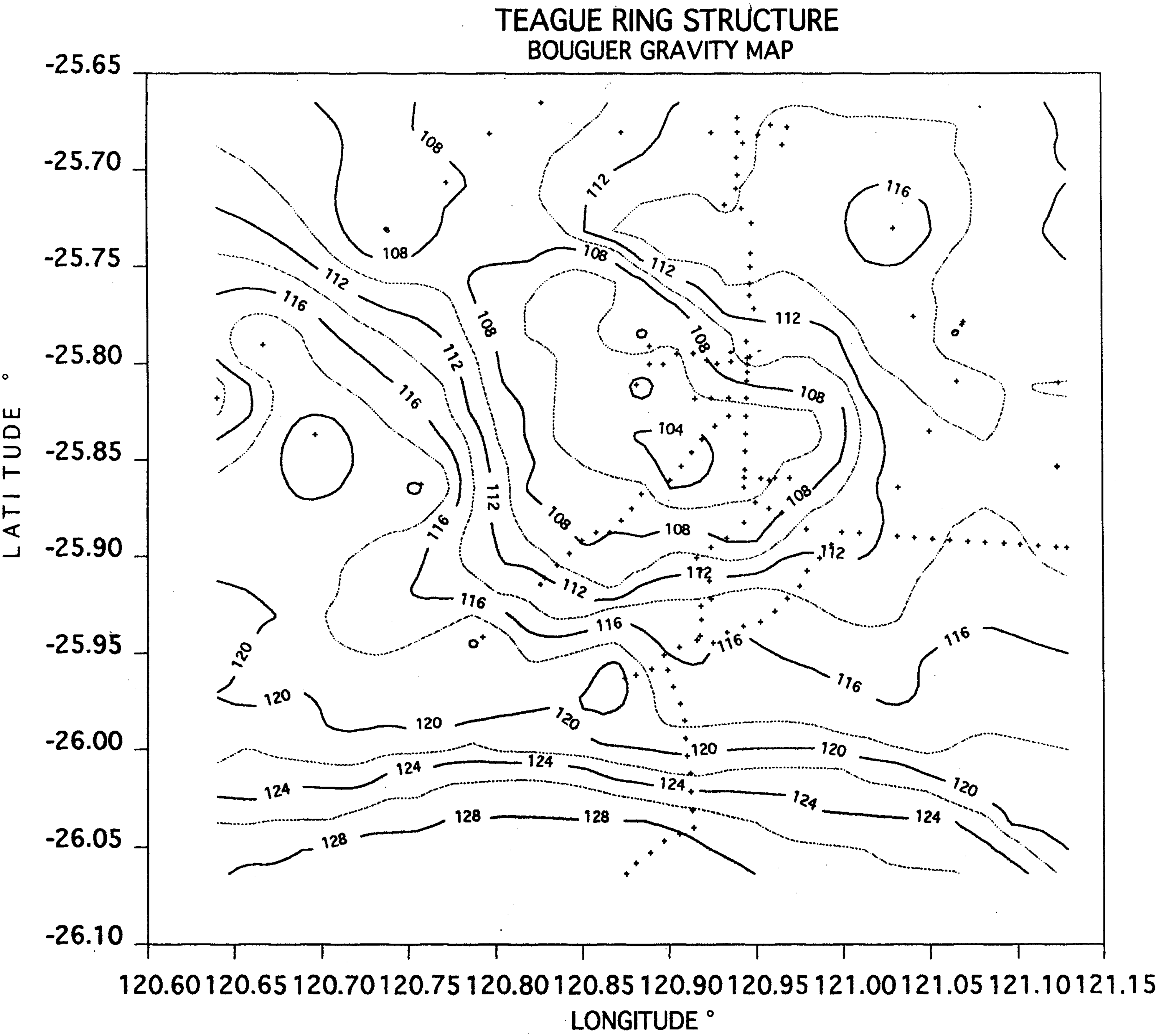

TEAGUE RING STRUCTURE
BOUGUER GRAVITY MAP
-25.65
-25.70
-25.75
-25.80
-25.85
-25.90
-25.95
-26.00
-26.05
-26.10
LATITUDE °
120.60
120.65
120.70
120.75
120.80
120.85
120.90
120.95
121.00
121.05
121.10
121.15
LONGITUDE °
104
108
112
116
120
124
128

Figure 5a

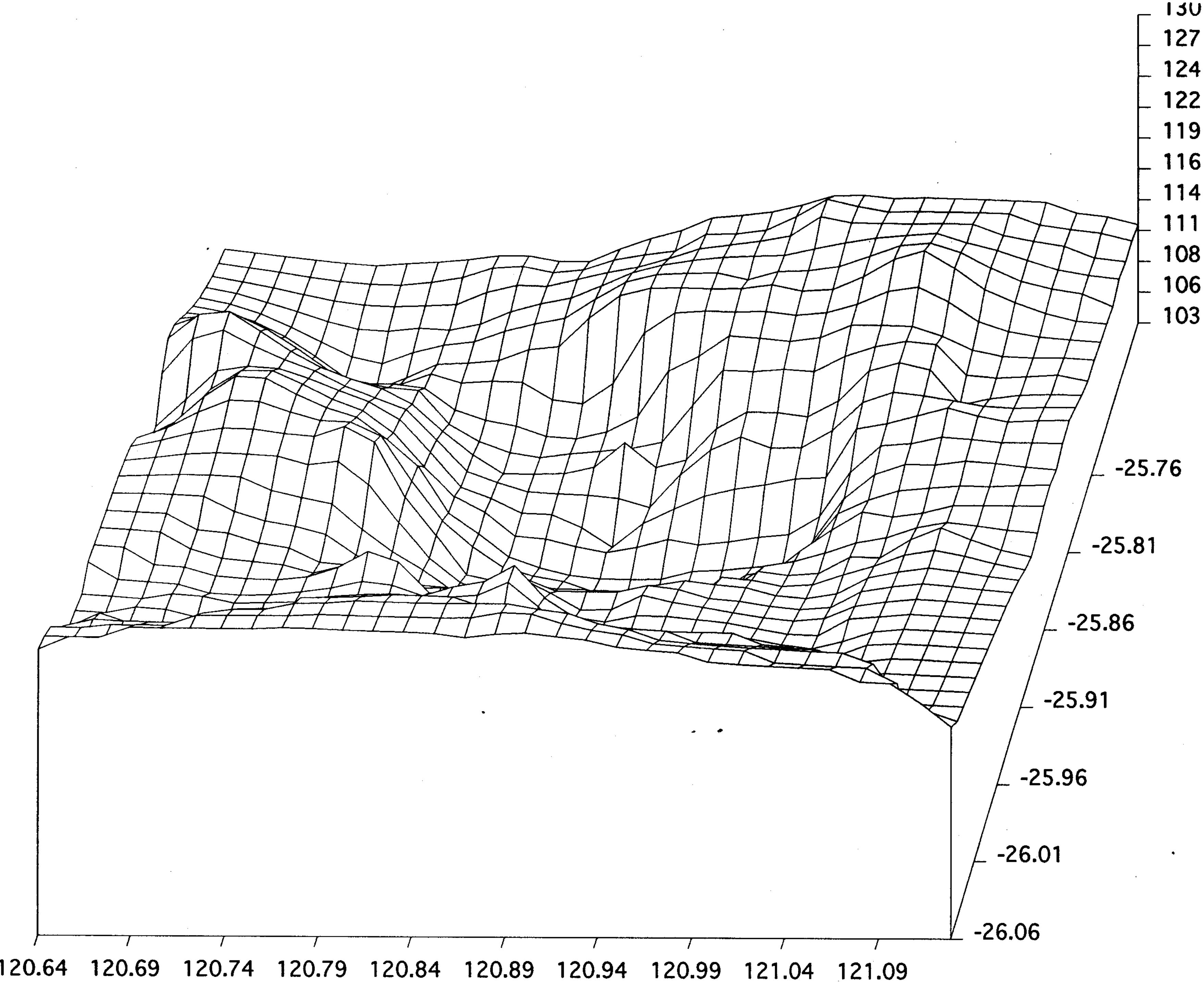

130
127
124
122
119
116
114
111
108
106
103
-25.76
-25.81
-25.86
-25.91
-25.96
-26.01
-26.06
120.64
120.69
120.74
120.79
120.84
120.89
120.94
120.99
121.04
121.09

Figure 5b

TEAGUE RING STRUCTURE
1ST ORDER RESDIUAL MAP

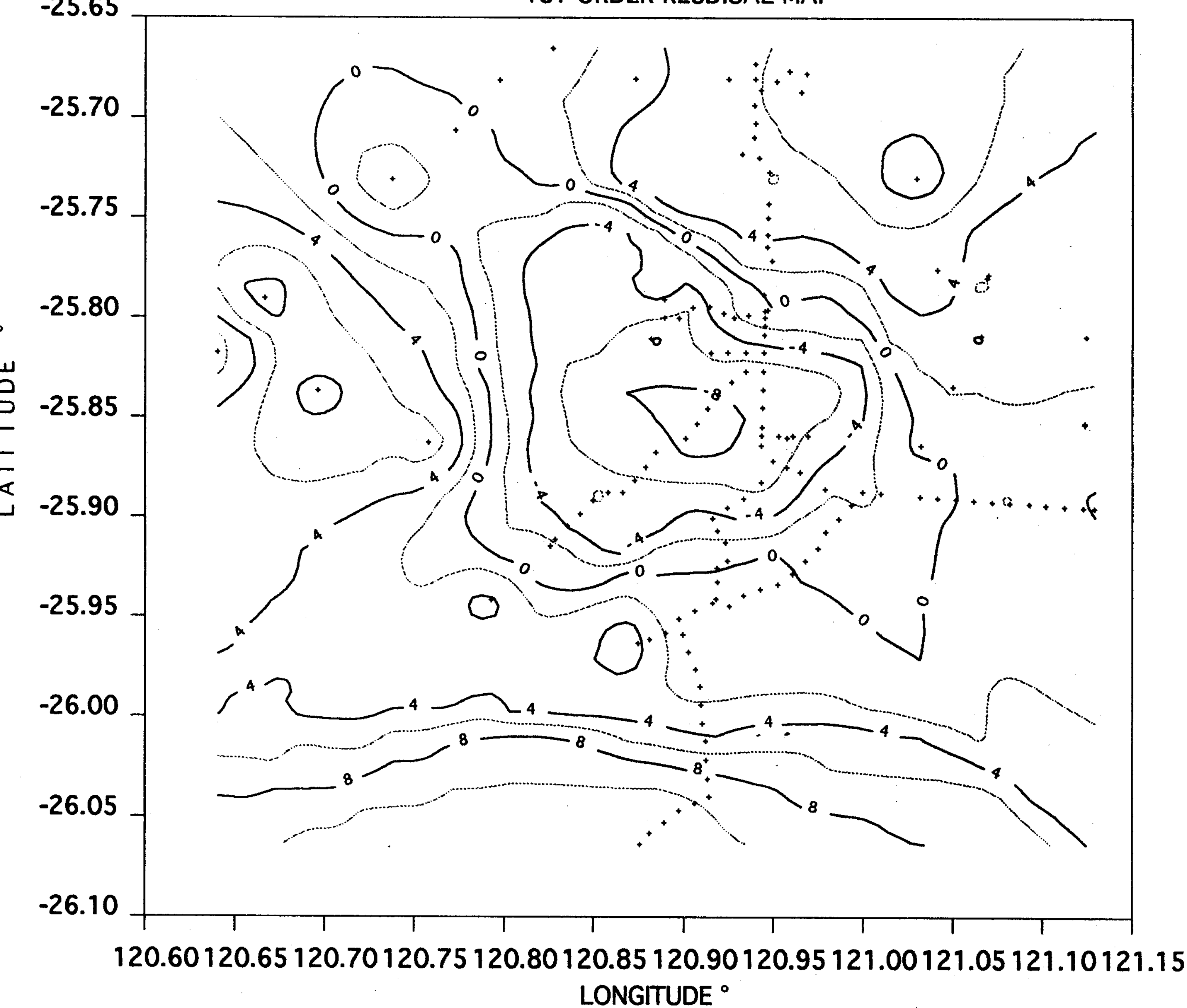


Figure 6a

TEAGUE RING STRUCTURE
1ST ORDER RESDIUAL MAP

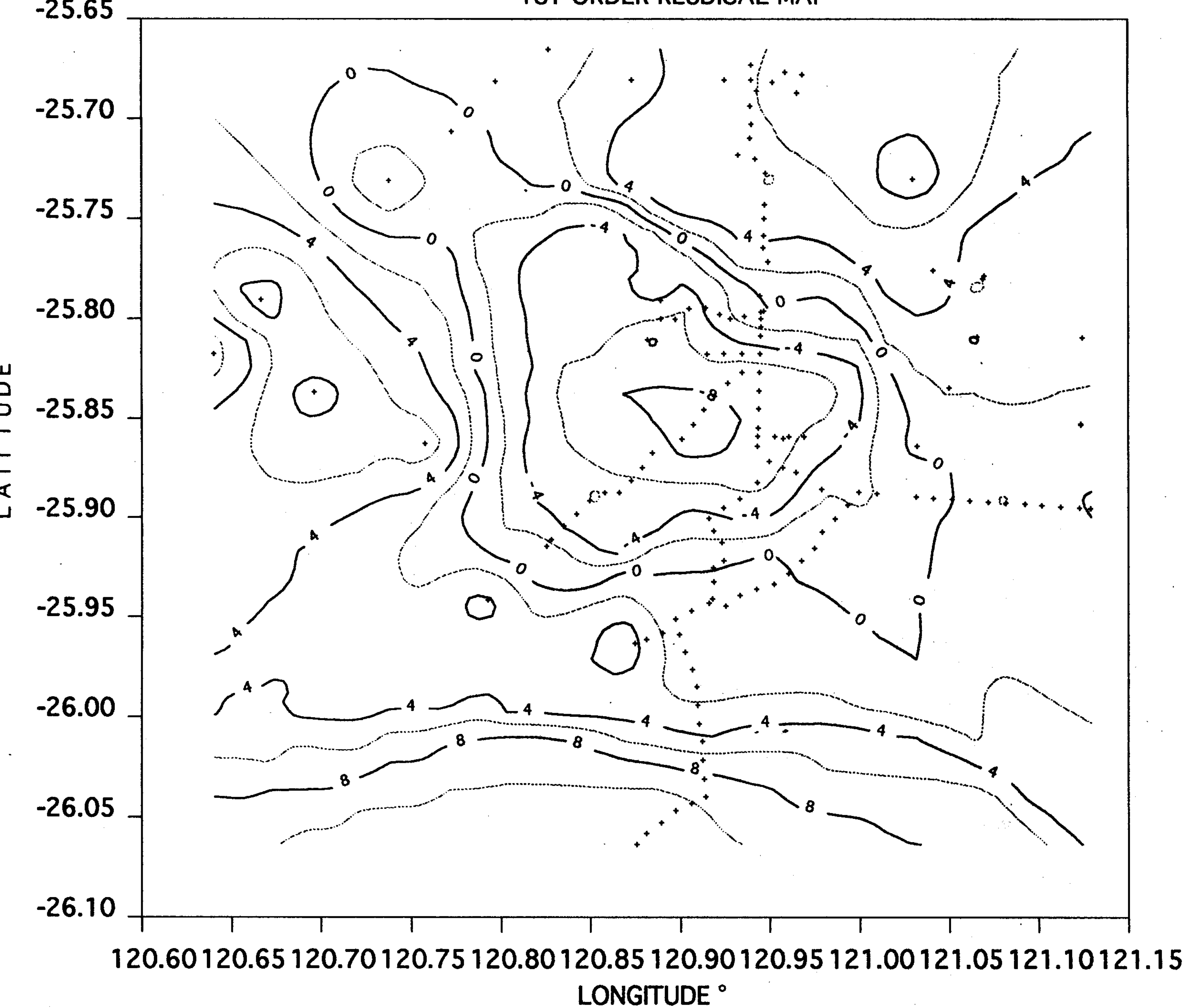
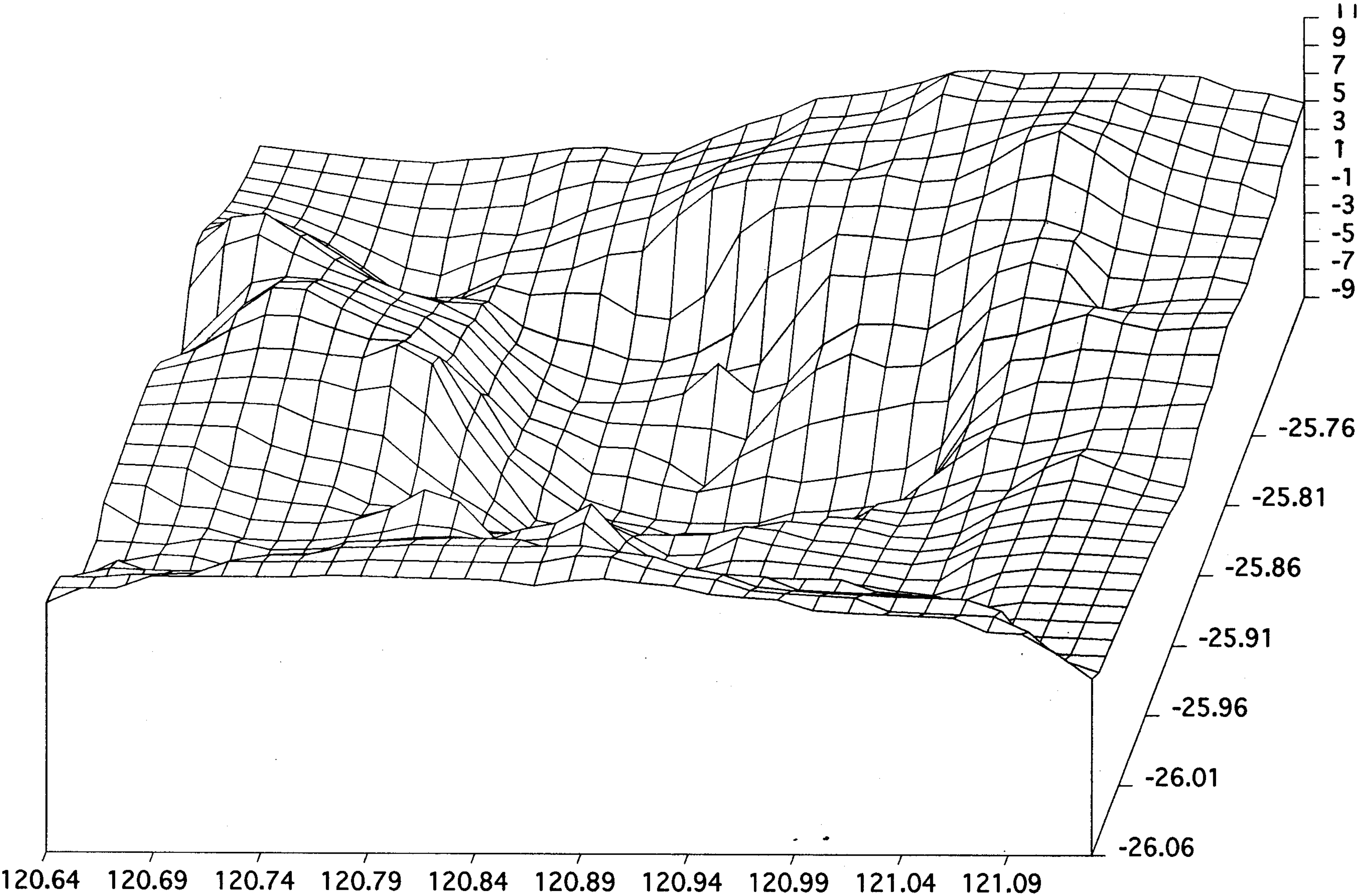
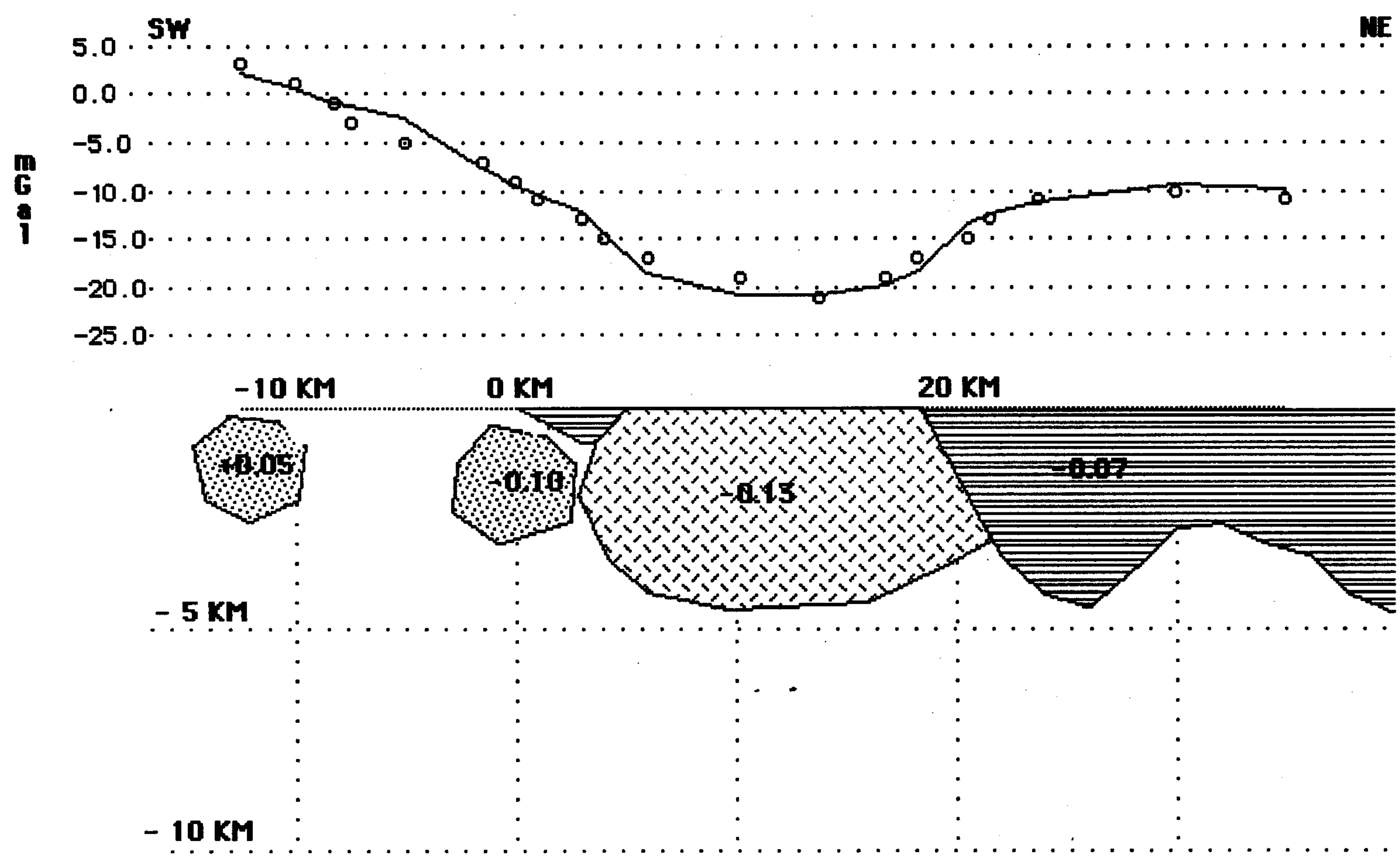
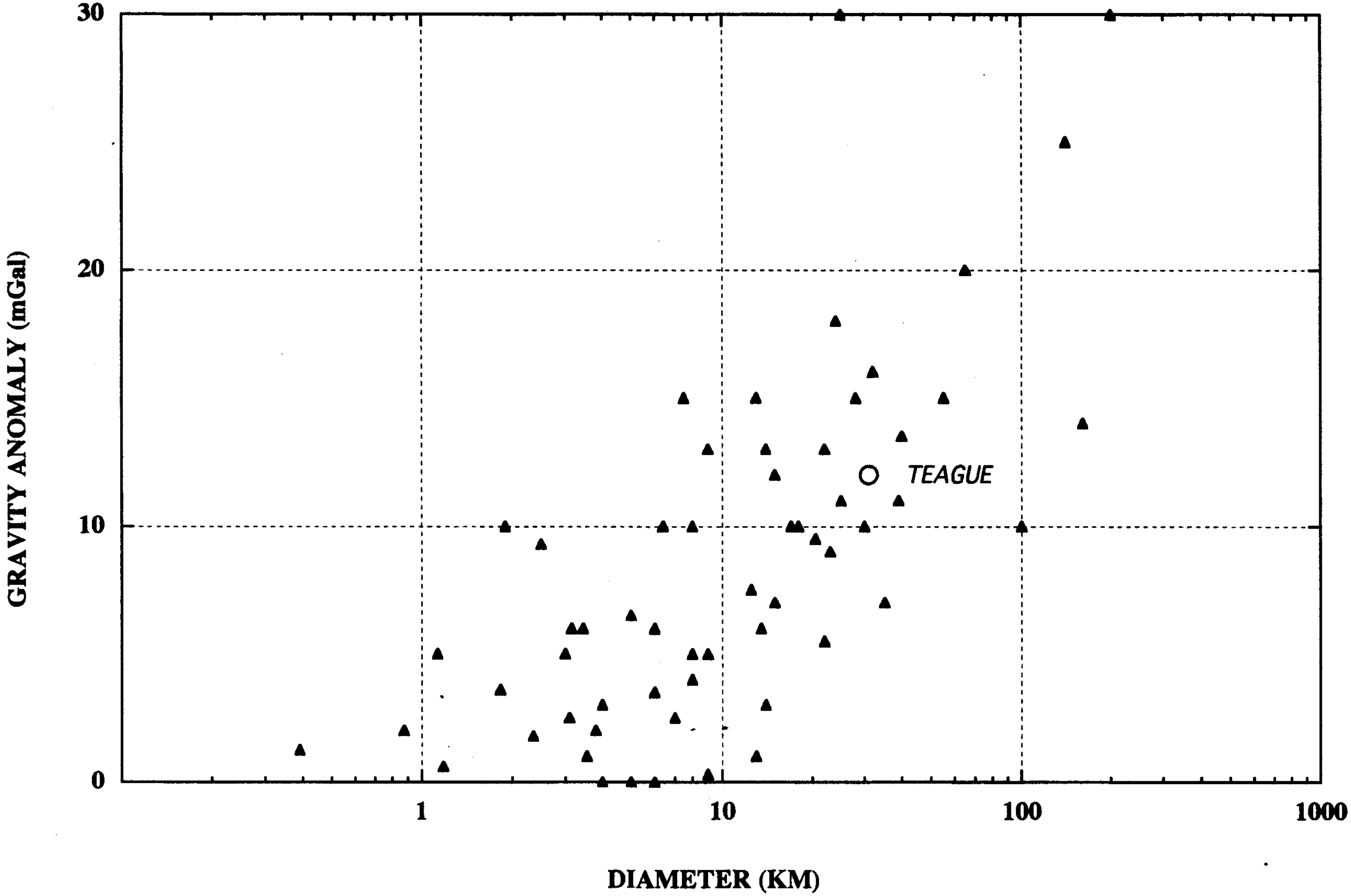


Figure 6a


11
9
7
5
3
1
-1
-3
-5
-7
-9
-25.76
-25.81
-25.86
-25.91
-25.96
-26.01
-26.06
120.64
120.69
120.74
120.79
120.84
120.89
120.94
120.99
121.04
121.09


SW
NE
mGal
5.0
0.0
-5.0
-10.0
-15.0
-20.0
-25.0
-10 KM
0 KM
20 KM
+0.05
-0.10
-0.15
-0.07
- 5 KM
- 10 KM



GRAVITY ANOMALY (mGal)
30
20
10
0
1
10
100
1000
DIAMETER (KM)
TEAGUE

Figure 8